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VOLUME 21
No. 1 — 1956

32 VICTORIA ST
LONDON, SW1

Annual Subscription to Non-Members - £2.2.0
Price per Number to Non-Members - 5s. 0d.

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Session 1955-1956

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Presidential Address

The Society and the Citizen

By A. G. HIGGINS, M.Sc., F.R.I.C. *(Fellow)*

Introduction

I would like to commence this address by acknowledging with sincere gratitude the honour you have conferred upon me by electing me to be your President for the ensuing year. I regard it not only as a personal compliment but also as a tribute to the great Industry I have been proud to serve for 26 years. I follow a line of distinguished Presidents and nobody is more conscious than myself of the difficulty of maintaining the high standards which they have set, but I shall do my best to emulate them. Since it is some 12 years since I was actively engaged as a lighting engineer I have found some difficulty in selecting a suitable subject upon which to base an address to an audience, including, as it does, so many well informed lighting engineers, but I thought it might be useful to consider the ordinary citizen and review the ways in which the activities of our Society impinge upon and affect his mode of life.

Consideration of the objects of the Society, as propounded by its first President, Professor Sylvanus P. Thompson, and as later incorporated in our Memorandum of Association, indicates that our terms of reference are wide and include "the advancement of the utilisation of natural and artificial light and the dissemination of knowledge relating thereto." It may truly be said that we are interested in all aspects of lighting and of seeing and must therefore be concerned with matters which vitally affect the ordinary citizen. Let us therefore consider how the Society has helped the citizen to take the fullest advantage of the wonderful gift of seeing.

Natural Lighting

In the first place, the greater part of his working hours are spent under conditions of natural lighting. This is a subject to which considerable study has been devoted by many prominent members of the Society, outstanding among them being the late P. J. Waldram, whose pioneer work on the proper distribution of daylight in buildings is rightly regarded as classic. In 1951, J. G. Holmes devoted his Presidential Address to the study of natural lighting and in this fascinating address the whole subject was so exhaustively treated that further reference on my part is unnecessary. I would only recall that in Part III of the Society's Code for Lighting in Buildings, there are summarised in a readily comprehensible form the results of the researches of many of our members over a long period of time. In addition to the Code, the Report on the Lighting of Buildings of the Lighting Committee of the Building Research Board contains excellent advice in regard to the principles of design for daylight. Thus, there is available to the citizen a wealth of information on the proper distribution and use of natural lighting in buildings according to the purposes for which those buildings are to be used.

Artificial Lighting

Our citizen must also spend many hours of his life under conditions of artificial lighting, and it will be interesting to consider the tremendous benefits which are bestowed upon him by reason of the remarkable developments in lighting technique during the last two decades, provided he is in a position to take advantage of them.

Presented at a meeting of the Society held in London, October 11, 1955.

Lighting for the Citizen in the Home

Perhaps the obvious place to consider first is the home. Here, I fear, the situation is frequently far from satisfactory. The Report on the Lighting of Buildings gives details of a survey made on a number of dwellings of the lower income groups, which revealed that the quantity of artificial light employed was in general well below the standards recommended in the Society's code. The report also draws attention to the powers given to local authorities under Section 6 of the Housing Act, 1936, whereby they may, and if required by the Minister shall, make and enforce by-laws for securing adequate lighting of all rooms in working-class houses. As far as I am aware, no authority has of its own initiative exercised these powers nor has there been any direction from the Minister to this effect. Further, as P. V. Burnett pointed out in a discussion at a meeting of the Society in 1942, even were such legal steps taken their enforcement would be impracticable. Moreover, the Act does not relate to flats which are, of course, steadily increasing in number. My own feeling is that progress in this matter is best effected by educative means, and here the Society can play an important part.

Rapid strides have been made in recent years in the development of luminaires suitable for lighting the home, and, with the wide range of fluorescent lamps and incandescent tubular lamps now available, it is possible to produce some delightful decorative effects as well as providing excellent illumination. In considering lighting of the home, we should not always think in terms of luminous output and maximum efficiency of utilisation. The late Sir Clifford Paterson once reminded us that we do not always desire to be flooded with light; there is something to be said, on certain occasions, for soft, restful lighting from fittings where the utilisation factor may be relatively low.

Many of these modern developments are not, however, readily available to a large number of our citizens living in dwellings owned by local authorities who, for obvious reasons of economy, supply the bare essentials for the provision of adequate lighting, usually a point in the centre of the ceiling and one in the skirting board. The latter all too frequently, although needlessly, is monopolised by radio or television. If, therefore, our citizen desires to take advantage of these modern developments, he is faced with a considerable capital outlay, not only for the more expensive fittings themselves, but also for additional electric points which he will have to leave for any succeeding tenant. There is naturally some consumer resistance to capital expenditure of this nature. Moreover, he is frequently precluded, by the terms of his tenancy, from channelling the walls to install the additional points. I do not make these observations by way of criticism of local authorities, who quite clearly have a duty to impose such conditions as they deem necessary to protect from damage the property for which they are responsible, but only to illustrate that in the domestic field the citizen may find it difficult from economic considerations and other limitations to take the fullest advantage of recent developments in lighting technique.

Lighting for the Citizen at Work

Our citizen, being a normal person, must work and he must play. Unless he is an agricultural worker, he will normally be employed in some environment where artificial lighting will be involved for some part of his working hours, perhaps in an office or a factory or a shop. If he is a factory worker he will, in theory at any rate, be ensured of adequate lighting, for the Factory Acts and the regulations made under them provide not only for minimum standards of illumination, the absence of glare and the avoidance of undesirable shadows, but also for their enforcement by inspectors of factories. Curiously enough, the regulations make no direct reference to evenness of illumination, and this has often seemed to me of considerable importance in certain

locations, some parts of gas works for instance. Indeed, so far as the prevention of accidents is concerned, the distribution of light in such locations is, perhaps, of greater consequence than the actual level of illumination.

In the field of industrial lighting, however, the advantages of modern discharge light sources have been exploited to a marked degree, for here the relative values of capital outlay and running costs are considered in truer perspective than is the case in the home. A former President of the United States, Woodrow Wilson, in a speech in 1916, said "the thing to do is to supply light and not heat." He was of course referring to political light and heat; as a servant of the Gas Industry, I would disagree profoundly with such advocacy. From the viewpoint of illuminating engineering, however, he was undoubtedly right and I wonder whether he could have envisaged the development of the discharge lamp as a source of illumination. The much higher luminous efficiency and the lower radiant heat from such a source compared with other sources have rendered it eminently suitable for industrial lighting.

The Society has provided a platform for many excellent papers on the lighting of factories of many kinds, nor must we forget the studies relating to the effect of illumination on productivity and to visual acuity, undertaken by a number of investigators, much of whose work has been discussed at our meetings.

There are no doubt many factories where lighting is still of a lower standard than we should deem desirable, but I venture to suggest that the work of the Society and of its members individually during the last two decades is rapidly bearing fruit and there are thousands of workers employed in factories where lighting standards are high and seeing conditions extremely comfortable.

Before leaving the subject of factory lighting, I ought to refer to the special problems with which the lighting engineer is faced in lighting factories where a hazard arises from the manufacture or use of explosive or inflammable substances. This subject was studied in some detail by a sub-committee of the National Illumination Committee of Great Britain and its report was presented and discussed at the Zurich meeting. Further, we have had before the Society some excellent papers dealing with various aspects of the problems involved. Similarly, the lighting of coal mines presents difficulties peculiar to the work carried out in them and here too the Society has provided the platform for a number of valuable contributions.

It is a curious anomaly that while workers in factories are to some extent cared for by Statutory Instruments and Regulations made under authority of an Act of Parliament, no such provision has yet been made to ensure adequate lighting for those working in offices. In 1952, however, the Building Research Board published the Report of its Lighting Committee on The Lighting of Office Buildings, in which standards of lighting, both natural and artificial, based largely upon the I.E.S. Code, were prescribed. Enquiries made by the committee at that time showed that there were many offices in which the standard of illumination fell well below the recommended values. No regulations have as yet been passed which will ensure the implementation of the recommendations in the report, but I feel that the publication of the report will lead to gradual improvement and the Society can do much by the educative means available to it.

A statement has recently been made in the daily Press that the Government intends to introduce legislation relating to conditions of employment in various non-industrial occupations. These conditions will no doubt include lighting and it may well be that in this connection cognisance will be taken out of the Report on the Lighting of Office Buildings

Workers in shops are usually provided with ample light, for tradesmen are generally alive to the commercial attraction of well illuminated premises. It has been argued in some quarters that workers in shops spend an undue proportion of time under artificial lighting, but I doubt whether, in view of the adequacy, both in

quantity of the illumination usually provided and of the quality of the lighting, this is really a serious hardship. Not all workers in shops, however, spend their time in the areas where sales are transacted, but many must work in kitchens, offices, packing rooms and store rooms and it is in such places that the lighting may be considerably less lavish. The Shops Act, 1934, requires "sufficient and suitable lighting" in all parts of shops, but gives no guidance as to what is suitable or sufficient nor does it apparently empower any Minister to prescribe actual standards of illumination. Here again is a field where the continued good work of the Society can help to effect improvement and indeed the recommendations of the Society as embodied in its Code, for example, might well form a basis upon which the courts could adjudicate in the case of a dispute.

This very general and necessarily brief review of the fields of employment in factories, offices and shops covers by far the larger proportion of the working population, but there are other occupations as in road transport, aviation, railways or shipyards, with which particular lighting problems are associated. Without pursuing these problems in detail, it would be safe to say that the Society or *Light and Lighting*, with which the Society is so intimately connected, have at various times dealt with them and have disseminated knowledge relating to them. Thus I feel that the rapid strides which have been made in the art and science of lighting during the last two to three decades and the work of the Society in fulfilling its function so admirably epitomised in its motto *Passim Spargere Lucem*, have greatly improved the lot of the ordinary citizen in carrying out his daily task.

Lighting for the Citizen's Leisure

Since the war, there has been a general tendency for working hours to be shorter and for citizens to enjoy longer periods of leisure. The part that lighting has played in enabling them to make the most of that leisure is tremendous. Indeed, I would say that it is in the fields of entertainment and sport that the lighting engineer has been able to exploit as fully as anywhere the science and art of his profession and many of our more successful meetings have been those at which papers concerned with these matters have been discussed.

What a vital contribution to the successful production of any theatrical performance is made by the lighting effects, be it an opera, a straight play or a lavish musical comedy! And what a variety of apparatus is available to the lighting engineer to enable him to produce these effects!—tungsten filament sources with numerous coloured screens, fluorescent lamps of various hues, ultra-violet radiation with fluorescent materials and so on. The effective application of these sources for theatre lighting not only calls for a high measure of technical skill and knowledge but also requires an artistic flair.

If we like concerts, consider what a contribution the lighting of the Festival Hall makes to the atmosphere of this unique auditorium, surely one of the most restful of places in which to listen to good music. Even the Albert Hall, for which many of us have a great affection, in spite of its acoustic deficiencies, uncomfortable seats and overbearing proportions—even this has been improved tremendously for the concert goer by the introduction of the pale blue sounding board which also houses a most effective lighting installation. If visiting museums or picture galleries is our bent with what elation and enlivened interest are we able to enjoy the masterpieces of past and present generations when they are sympathetically lighted by modern installations especially designed for the purpose.

Not all of us enjoy concerts and museums, but most of us visit the cinema from time to time and in connection with the lighting of cinemas, the Society has played an important part. Papers dealing with projector lamps have been discussed at our meetings and as long ago as 1919, the Society considered the question of eye strain in

cinemas. Its recommendations were accepted by cinema licensing authorities and since that time, further investigations have been made by the Society at the request of these authorities. Indeed, at the present time an investigation is being made upon the effect on eye strain of the introduction of much wider screens.

Our citizen must not only have his aesthetic appetite satisfied; he also requires some physical exercise. He wants to box, to swim, to play football, tennis or badminton and when he is too old to do these things himself he likes to enjoy the excitement of seeing others do them. It is only in recent times that lighting installations have been satisfactory for the full enjoyment of these pastimes in hours of darkness and I would commend to those not already aware of it the very comprehensive summary given in M. W. Pierce's paper to the Society in 1953 on Sports Lighting.

Lighting Schools for the Citizen's Children

Let us now turn to other aspects of the citizen's life. If he has children, they will be required by law to go to school and no matter to what type of school they are sent they will be, to some extent, affected by the Education Act of 1944. Indeed, the effect of this Act upon the large majority of future citizens is profound and for this reason few Acts of Parliament have given rise to greater debate and comment.

I do not propose to discuss the matters over which there is so much controversy, for most of the difficulties arising from them will disappear in time. The full implementation of so ambitious a programme of education as the Act envisages is likely to take a generation to achieve, as indeed was acknowledged by the Minister who introduced it. I wish to refer to-night only to its effect upon the lighting of schools. The Standards for School Premises Regulations, 1951, made under authority of Section 10 of the Act provide, among other things, for minimum levels of illumination by daylight and by artificial light, for the absence of glare and for the avoidance of excessive contrast between lighting fittings and their background.

In framing these regulations, the Minister was undoubtedly strongly influenced by the Report on the Lighting of Buildings, to which I have already referred, and although the minimum standards specified in the regulations are rather lower than those recommended, there is no doubt in my mind that in all of the many new schools built since the war and in many that have been modernised, the standard of both daylight and artificial light is satisfactory. A study of two excellent papers given to the society in recent years by architects, "Lighting in Schools" by Anthony Pott and "Colour in Schools" by David Medd, will suffice to indicate the trends in regard to lighting in modern schools and few will dispute the assertion that from this point of view at least our citizens' children enjoy amenities of a high order compared with those under which their forebears studied.

Outdoor Lighting for the Citizen

Our citizen of course pays rates and taxes of some kind or other and these increase as more and more of his daily activities become the direct concern of the Welfare State. A certain proportion, many would argue far too small a proportion, of these contributions is devoted to the provision and maintenance of street lighting, a subject to which the Society and the Association of Public Lighting Engineers have devoted a great deal of time and energy. It may perhaps seem odd that so important an aspect of our national life as street lighting should not be the subject of some comprehensive legislation, but the fact remains that apart from London and Scotland there is no compulsion about street lighting. It is true that the Public Health Act, 1875, empowers highway authorities to light streets under their control, but does not require them to do so. The Metropolis Management Act, 1855, requires the highway authorities in the Metropolitan area to light their streets "well and sufficiently" although it is not at all clear as to who shall decide as to the interpretation of the words "well and

sufficiently." In Scotland also there are a number of similar Acts governing various cities which refer to the provision of street lighting, but in an equally ill-defined manner.

The Road Traffic Act, 1934, gives county councils power to provide illumination on country roads, but not until the lighting authority has had a reasonable opportunity of complying with their requirements. The Trunk Roads Act, 1936, transferred to the Minister of Transport certain of the principal roads in Great Britain in respect of which the Minister became the highway authority. One sub-section of this Act empowers the Minister to illuminate or to improve the illumination of such roads. An obvious advantage of such powers is that the lighting of important thoroughfares may be achieved by the use of a properly planned installation and not as the result of a series of independent installations of varying effectiveness and often of different light sources. Further, the standard of illumination provided can be such as would be beyond the financial resources of many of the smaller lighting authorities through which the roads pass; on the other hand, it means that a substantial mileage of highways now comes under the care of one authority—the Minister of Transport, and in times of rapid development a heavy responsibility falls upon the officials who have to advise him in these matters to ensure that the most appropriate system is employed.

Since the publication in 1937 of the Report of the Departmental Committee of the Ministry of Transport on Street Lighting, a committee of the British Standards Institution has been working hard to produce codes of practice based upon the recommendations contained in the report. In the first place, the committee was appointed to consider a revision of the existing British Standard for Street Lighting, universally acknowledged as out of date in view of current developments, and for several years it laboured under the patient chairmanship of the late Sir Clifford Paterson to produce a satisfactory standard. The conflict of opinion, however, was so great that the project was abandoned in favour of a Code of Practice, Part I of which relating to traffic routes was published in 1952 and Part II dealing with other roads it is hoped will be available shortly.

The fact that these codes have taken 15 years to complete is, I think, indicative of the difficulties of the problem, many of which were related to the establishment and correlation of the factors involved in visibility at night; others were due to personal prejudice. During the 20-odd years that I have been associated with the Society, numerous theories have been put forward in connection with street lighting, almost as many theories as there were light sources, and I have often been reminded of the famous lines in Omar Khayyam's Rubaiyat :—

> "Myself when young did eagerly frequent
> Doctor and Saint and heard great argument
> About it and about, but evermore
> Came out by the same door wherein I went."

Nevertheless, these codes are worthy documents and represent years of patient investigation and research. Their implementation by highway authorities should do much to improve road safety by night.

We live in a competitive age in which our citizen is subjected to a flood of advertisement telling him what to drink, what to eat and how to cook it, how he should spend his leisure, how he should cure the many aches and pains from which it is assumed he is bound to suffer and so forth. Lighting plays its part in this commercial activity, and the centres of many of our cities and towns are at night bedecked with a mass of coloured, glaring, flashing and scintillating signs vying with each other to catch the public eye. These, I am bound to confess, are for the most part, quite unpleasing to me, and for this reason I have always thought Piccadilly Circus a place to be avoided at night. I imagined it impossible to concentrate more unwanted

lumens in a specific area than are to be found at Piccadilly Circus, until I saw Times Square in New York. Here was so much light from blazing signs as to be painful to the eye. Here, I thought, was the commercial misuse of highly scientific apparatus at its worst. But I must hasten to acknowledge that I find myself rather a lone wolf in this direction. That these signs achieve their purpose there can be no doubt; they do so with aggressive efficiency. Moreover, the majority of our citizens like them immensely. Whenever there is an opportunity to celebrate, they throng to these centres, the Londoners to Piccadilly Circus and the people of New York to Times Square. There they find the right atmosphere, to which, no doubt, the signs contribute, for the carefree and happy abandon they seek. I should not wish to leave the impression that I am averse to the use of lighting for purposes of publicity, but I feel that the commercial value of luminous signs would not be decreased, but on the contrary considerably enhanced, if greater efforts were made to see that they toned in with and contributed to the general amenities of the surroundings in which they are used. I am sure I cannot do better in this connection than to recall the excellent paper given at our Southport summer meeting by the late André Claude on "The Decorative Approach to Commercial Lighting."

In sharp contrast to the displeasure with which I regard much of the commercial lighting one sees in cities and towns, I must express my keen appreciation of the delight which is afforded by the flood-lighting of so many of our beautiful public buildings. Here the lighting engineer has shown the utmost skill, and has made manifest many of the fine architectural features of some of our buildings which hitherto have not been fully appreciated. Flood-lighting, at one time employed only for specific celebrations and occasions, is more and more becoming a permanent feature of the life of cities and towns, and must be the source of a great deal of pleasure to their citizens.

The Society's Contribution in the Future

So in his work and in his play the rapid progress in lighting technique, both by day and night, has had a profound influence upon the ordinary citizen. The Society may rightly be proud of its contribution to our national life, and we may feel with justification that the objects for which the Society was founded are being amply fulfilled. But we must not leave it there and rest upon our laurels. We have established not only a right but, what is more important, a responsibility to continue and to increase our contribution to the wellbeing of the public.

Here, I suggest, we might perhaps with advantage review our terms of reference and see whether they are appropriate to our present and foreseeable needs. Should we perhaps cast our net wider and endeavour to bring into our deliberations and discussions people who would not necessarily regard themselves as illuminating engineers but whose activities are closely associated with lighting, people in whose work lighting plays so vital a part? We have long since recognised the desirability of close association with architects. Ought we not to try to collaborate with others such as, to quote one example, specialists engaged on the internal decoration and furnishing of premises of various kinds? The late J. S. Dow, in his presidential address, invited us to attempt a more positive approach to the many users of light from whom we might learn much in regard to the application of light within their special fields.

I would agree with Mr. Dow in this and in his assertion, repeated by so many of my predecessors, that the decision of the founders of the Society to create an Illuminating Engineering Society and not a Society of Illuminating Engineers was right. But no society can stand still for long, either it must progress or decline and conditions prevailing to-day are different from those which operated when the Society was formed. We may perhaps consider that our title is not altogether appropriate

to our present requirements, particulary in view of the restrictive meaning which by usage and indeed by definition in a British Standard is now applied to the word "illumination." Further, many of our members are not "engineers" in the sense in which the term is normally accepted.

On the other hand, we have lived for 46 years with our present name; we have built up a reputation and a tradition of service of a very high order which we must guard with the utmost jealousy. We must be quite certain that it we felt it desirable in order to increase the scope of our activities that some change be effected, our goodwill would in no way be jeopardised.

We are also faced with the problem of satisfying the needs of the professional lighting engineer. Dr. Walsh dealt with the training of the illuminating engineer in his presidential address in 1947. He showed how the progress of the art and practice of lighting had given rise to the necessity for properly trained professional men. There are those who assert that a cultural organisation cannot properly include professional men in its ranks and there are those who would have the Society converted into an Institution of Illuminating Engineers. This, I feel, would be a mistake and I see no reason why it should not be possible to continue, and indeed considerably to extend, our cultural functions, while at the same time providing for the professional man.

What are the qualifications required by the professional lighting engineer and how can the Society help the young man in industry to acquire them? Firstly, it is essential that he shall be acquainted with the scientific principles involved in the production, distribution and utilisation of light. This aspect was most fully covered by Dr. Walsh in his presidential address. Appropriate courses of instruction may be provided at technical colleges and examinations may be set to cover these technical requirements. The scientific aspect, however, is not sufficient, for the lighting engineer must know something of the art as well as the science of lighting. J. M. Waldram's presidential address, "Beyond Engineering," was particularly concerned with the artistic attributes which are a necessary adjunct to technical skill in most fields of lighting. These attributes are, however, very difficult to define and some native aptitude may underlie their most successful cultivation. Experience, however, is of paramount importance and the Society can best help the young lighting engineer by encouraging him to attend meetings, either in London or at the Centres and Groups, and by ensuring that the programmes include a reasonable proportion of papers relating to the artistic aspects of lighting practice. By listening to the experts, the student may glean much from their experience.

There are many of our members, particularly in some of the Centres, who feel that the Register of Lighting Engineers, which represents the Society's first attempt to satisfy the requirements of the professional man, does not quite meet the situation and the council has the matter under active review.

Whatever regulations, however, are drawn up by the Society for a professional qualification in lighting, it can only ensure an appropriately high standard of knowledge and attainment. It cannot by itself confer status. The status which the qualification eventually achieves is directly related to the degree of its acceptance by the lighting industry and of course by users generally. Here I would reiterate Dr. Walsh's plea to our Sustaining Members and to other employers of lighting engineers, to do all in their power to encourage their staffs to acquire the Society's qualification, to assist them in their training and to recognise the qualification as an essential requisite for those engaged in the various spheres of lighting practice.

The adoption of such a policy would rapidly endow the qualification with the status that the Society desires, that the standards of academic and practical achievement certainly warrant and that the industry itself would find profitable.

It has been suggested that some of our larger Sustaining Members provide their own schemes of training based upon their particular requirements. These are

frequently associated with study for corporate membership of The Institution of Electrical Engineers or some other appropriate professional institution. Such schemes are of course excellent, but I can see no reason why the Society's qualification should not be taken concurrently.

There is a parallel situation in the Gas Industry which requires the services of civil, mechanical, electrical and chemical engineers, chemists and physicists as well as gas engineers. Many in authority in the Gas Industry have long felt that those employed in a technical capacity should possess a qualification appropriate to their particular duties—civil engineer, chemical engineer, chemist as the case may be, but that all technical personnel employed in the industry should also be corporate members of The Institution of Gas Engineers. The Education Regulations are framed in such a way that the examinations are conducted jointly with The Institution of Civil Engineers and negotiations are at present being undertaken with The Institution of Chemical Engineers to find a basis for the mutual acceptance of examinations of the two institutions as exempting qualifications. Further, the Higher National Certificate in Mechanical Engineering, which goes a long way towards Corporate Membership of The Institution of Mechanical Engineers, exempts candidates from a large part of the Associate Membership Examination of The Institution of Gas Engineers.

It would, I feel, be a great step forward if similar arrangements could be encouraged in the case of the Society's qualification, which might well become an essential requisite for all of those practising as lighting engineers, no matter what other qualifications they may possess. By such means, the lighting industry would help to ensure that the Society's qualification, whatever name it is eventually given, would achieve the measure of recognition that is undoubtedly its due.

Some Factors Affecting the Efficiency of Fluorescent Lamps—The Quest for Higher Luminous Output

By F. JACKSON, B.Sc., A.Inst.P. *(Member)*, R. MOLLOY and K. SCOTT, B.Sc.

Summary

The theoretical aspects of the dependence of the luminous output of fluorescent lamps on the efficiency of production of ultra violet radiation and its conversion into light by the phosphor are discussed, together with a review of the application of this knowledge to practical lamp making.

(1) Introduction

Because of their good colour characteristics, fluorescent lamps are rapidly replacing filament lamps for many lighting applications. If the filament lamp had been developed after the fluorescent lamp some consider that, because of its simplicity, it would have been hailed as a great achievement. Why then does the fluorescent lamp continue to gain in popularity? Besides the obvious advantages of higher efficiency, colour range and longer life, the fluorescent lamp's greatest asset is that its life is more or less unrelated to its efficiency. The luminous efficiency of tungsten filament lamps can only be substantially increased by reducing life, the efficiency/life relationship being well established. Because we require lamps of both higher efficiency and longer life any lamp in which these factors are inter-related has an insuperable limitation. During the last 10 years, not only has the life of the fluorescent lamp been increased. but its average efficiency throughout life has been steadily improved. With a lamp of this type improvements in life demand improved lumen maintenance, which is one aspect of higher efficiency and one which is of primary concern to the user.

Efficiencies that are theoretically possible are not at present being achieved and consequently lamps of higher efficiencies will continue to become available.

(2) Lamp Experience

A lamp in general use is often taken for granted. It is useful to set out what we know of the present fluorescent lamp range and its history, for these give clear indications of how further advances can be made, particularly with regard to higher light output.

Since the introduction of the 5-ft. 80-watt Daylight lamp some 17 years ago many new colours and lamp sizes have come into commercial use. Although increases in luminous efficiency of all sizes and colours have been made, the pattern of lamp efficiencies relative to lamp colour and size remains unchanged. Two 2-ft. 40-watt lamps will always give less light than one 5-ft. 80-watt lamp of the same colour, and the relationship between their light outputs remains constant when the efficiencies of lamps of that colour are increased. This same relationship applies no matter what colour of lamp is considered.

Lamps of certain colours are inherently more highly efficient than others, but it is also possible to have different efficiencies from lamps of similar colour appearance —New Warm White and De Luxe Warm White lamps are good examples of this.

The fluorescent lamp is affected considerably by the conditions under which it

The authors are members of the technical staff of Siemens Electric Lamps and Supplies, Ltd. The manuscript of this paper was first received on July 13, 1955, and in revised form on September 12, 1955. The paper was presented at a meeting of the Society held in London on November 8, 1955.

operates and the present designs have been developed largely because of existing climatic conditions and electricity supply voltages.

We know that 5-ft. 80-watt and 4-ft. 40-watt lamps mounted outside and unprotected on a cold winter evening give less light than normal and that the 40-watt lamp is the more adversely affected. Alternatively, at temperatures above normal the 40-watt lamp does not show, as a result of increases in temperature, the same reduction in efficiency as does an 80-watt. Such observations probably account for the discrimination between these two lamps shown by their respective choice in the temperature controlled buildings of America and the rather chilly halls of Britain.

Owing to the variation throughout this country of the electricity supply voltage, the regulations have had to require that lamps intended for 200-250 volt mains be capable of operation on a supply of 180 volts to give a safety factor of 10 per cent. when operating on the minimum voltage 200. Had the minimum required value been higher a larger lamp would probably have been developed with an increased arc voltage and a slightly higher efficiency.

Besides the above there are other lamp phenomena not generally known to the user; these will be described and a satisfactory explanation attempted.

However, as the fluorescent lamp requires starting and control gear and a suitable fitting we must not forget that the quest for greater lamp efficiency is not only a *lamp* problem, but a *lighting* problem and in consequence a compromise will be necessary.

(3) Fundamental Consideration

(3.1) Mechanism of Light Production by Fluorescent Lamps

In a fluorescent lamp light is produced by the discharge of electricity through mercury vapour, the resulting ultra-violet radiation exciting a fluorescent powder, or phosphor, to give the well-known luminous effects.

The lamp, consisting of a glass discharge tube coated internally with phosphor and with an electrode at each end, contains a small amount of liquid mercury and a few millimetres pressure of a rare gas, usually argon. The production of light depends mainly on the excitation of the phosphor by ultra-violet radiation. Electrons passing along the tube under the influence of an electric field collide with mercury and argon molecules, causing electrons in the outer orbits to occupy higher energy states or to escape from the atom completely. Such atoms can only remain excited for approximately 10^{-8} sec. and, as they revert to normal, energy is usually dissipated in the form of radiation of a definite wave-length. If the mercury vapour pressure and the excitation conditions are correctly controlled this radiation will be predominantly at a wave-length of 2,537 Å, but radiations of other wave-lengths are also produced and some of these appear as visible light through the phosphor layer. The ultra-violet radiation produced in this way impinges upon the phosphor layer on the interior of the lamp and causes it to emit visible light, the nature and quantity of which depends on the type of phosphor used.

As stated above, the electrons in the discharge collide with argon molecules as well as with mercury ones. These collisions are so numerous that the energy lost in this way can account for as much as 23 per cent.(1) of the total energy consumed in the lamp.

Energy is also expended in drawing electrons from the cathode and accelerating them to a velocity sufficient to excite the mercury atoms(2). This region of electron acceleration is referred to as the cathode fall; immediately beyond this and extending along the rest of the tube to the anode is the positive column. It is in this length that the collisions between particles take place which result in mercury ionisation, and over 60 per cent. of the available energy of a 4-ft. 40-watt lamp is dissipated here.

Of this energy about one-third is transformed by the phosphor into light and the remainder is lost as heat(1).

Thus, approximately 22 per cent. of the total lamp energy is emitted as light, and this includes the visible radiation produced in the mercury discharge.

The light output of a fluorescent lamp depends on the efficiency with which the discharge can produce 2,537 Å radiation and the efficiency with which the phosphor can transform this radiation into light.

(3.2) Factors Affecting Production of 2,537 Å Radiation

Since mercury is the source of the ultra-violet radiation its vapour pressure inside the lamp is of primary importance. Other factors affecting efficiency are tube diameter and length, gas pressure and the type of gas used.

(3.2.1) *Mercury Vapour Pressure*

We are all aware that the light output of discharge lamps is dependent on their operating temperature. The high-power mercury vapour lamp must run for 15 minutes to attain the necessary temperature for full light output; the sodium lamp requires inclusion in a vacuum jacket to reach optimum temperature and therefore maximum efficiency.

The fluorescent discharge lamp is no exception to this general rule(3). The temperature at which a lamp operates governs the mercury vapour pressure in the discharge column and on this depends the efficiency of production of 2,537 Å radiation. Many laboratories have made accurate assessment of the relationship between light output and lamp temperature(4,5,6,7).

Higher vapour pressures have the effect of promoting the multiple excitation of mercury atoms and the absorption of 2,537 Å radiation by unexcited atoms. Both these functions lead to the production of radiation of a longer wave-length at the expense of the ultra-violet emission. If on the other hand there is a complete absence of mercury there will be no 2,537 Å radiation produced at all. Somewhere between these extremes there exists an optimum pressure and this has been determined by many workers(4,5,6), who measured the light produced at various mercury vapour pressures keeping the current constant and controlling the temperature of the lamp by means of a water bath. It is generally found to be about 5 microns of mercury, which corresponds to a lamp wall temperature of 37 deg. C., but the curve has a very broad maximum as shown by Fig. 1, which was obtained from measurements on 80-watt lamps.

The curve of efficiency against tube current for a 1½-in. diameter tube, at a fixed

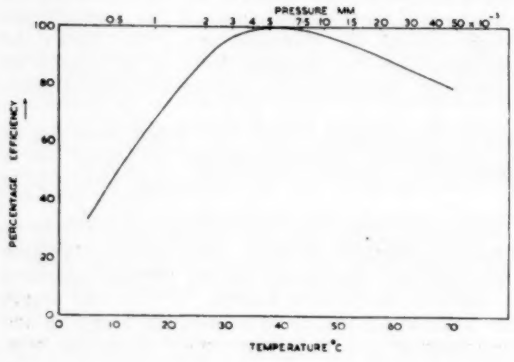

Fig. 1. Efficiency as a function of mercury vapour pressure (5-ft. 80-watt lamp).

temperature corresponding to optimum vapour pressure is shown in Fig. 2, curve A. Under normal operating conditions, however, the temperature does not remain fixed and an increase in current, for example, which causes an increase in temperature with a consequent increase in vapour pressure above the optimum will result in a reduction in efficiency. A decrease in current resulting in a decrease in vapour pressure below the optimum also causes a reduction in efficiency. A curve of efficiency similar to that shown in Fig. 2, curve B, will then be found.

(3.2.2.) *Tube Diameter and Length*

The 2 inches at each end of a lamp contribute little to its total light output. In a 5-ft. 80-watt lamp the energy lost at the lamp ends is about 13 watts and the same amount is lost at the ends of a 2-ft. 40-watt lamp which operates at the same lamp current. It is advantageous then for lamps to be as long as is convenient for use[8], so that these electrode losses will constitute the smallest proportion of the total lamp energy.

The effects of the tube diameter are concerned with the degeneration of discharge energy into heat. A narrow tube will cause increased losses due to ionic bombardment of the tube surface, called wall losses; on the other hand, a wide diameter tube will lengthen the path through which radiation will have to pass on its way to the phosphor and so increase the chances of absorption by unexcited atoms. In addition, it may be difficult to maintain the temperature of a wide tube for a given wattage loading, thus risking a fall in mercury vapour pressure and a consequent loss of efficiency. There exists an optimum diameter for a lamp whose current is specified, and this is

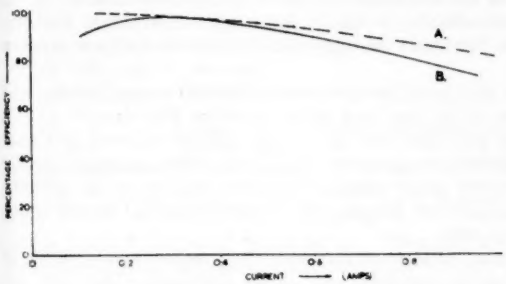

Fig. 2. Efficiency as a function of lamp current (4-ft. 40-watt lamp). A. At constant lamp temperature. B. At temperature determined by operating current.

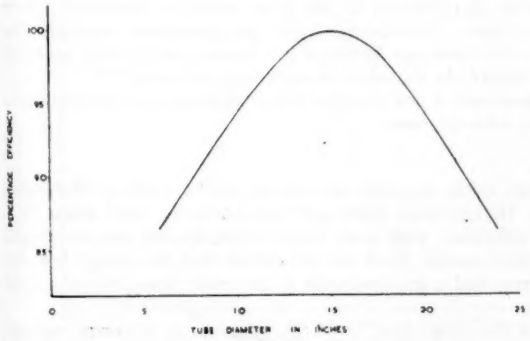

Fig. 3. Effect of tube diameter on efficiency (argon filling pressure 3 mm.; current loading, 0.4 amps).

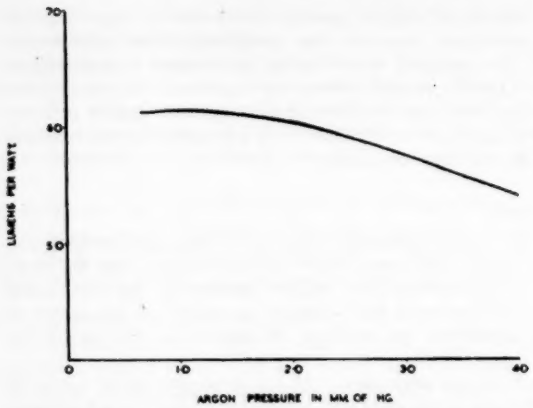

Fig. 4. Efficiency as a function of argon filling pressure (5-ft. 80-watt Daylight lamp).

indicated by the curve in Fig. 3, which shows the effect of tube diameter on positive column efficiency for constant current[9].

(3.2.3) *Gas Filling Pressure*

It has been found experimentally[10] that the efficiency of ultra-violet production in a lamp increases as the argon gas pressure is reduced down to a pressure of 1 mm. of mercury; below this pressure the efficiency drops away. Fig. 4 shows this for 5-ft. 80-watt Daylight lamps. The advantage of this effect is counter-balanced by the poorer lumen maintenance which attends it, and it has been determined that for lamps filled with argon the best performance throughout life is achieved with a pressure of around 3 mm.

Laboratory tests have shown that both the ease with which the arc is initiated and the life of the lamp are functions of the type and pressure of the filler gas[10, 11]. A lamp which contains too much or too little filler gas is very difficult to start, but once the arc has started a high gas content enhances the cushioning effect provided by the gas molecules, which prevents the high speed impact of mercury ions on to the cathode; were it not for this, rapid disintegration of the electron emissive material would occur, with consequent reduction of lamp life.

The reduction in lamp efficiency due to variation in gas pressure is a result of energy losses in the discharge due to electron and ionic collisions. At low gas pressures electrons can traverse long unimpeded paths through the discharge column, resulting in an increased number of collisions at the tube walls or electrodes where they dissipate their energy as heat. Conversely, high gas pressures increase the probability of collisions within the discharge between gas atoms and excited mercury atoms, which lose their energy before the emission of radiation can occur[12].

The pressure chosen is at best only a compromise which depends on considerations of life, lumen maintenance and tube diameter.

(3.2.4) *Type of Gas Filling*

In addition to argon, helium, neon, krypton and xenon can be used as filler gases for fluorescent lamps[13, 14]. Helium and neon are not normally used since they have been found to cause low efficiency with poor lumen maintenance characteristics, due mainly to the lightness of their atoms, for it can be shown that the energy transfer in a collision between an electron and a gas molecule is inversely proportional to the molecular weight of the latter.

A lamp using krypton as the filler gas[14, 15, 16] operates at a lower voltage

for the same running current than the corresponding argon-filled lamp; this causes a lower wattage loading of the tube and a consequent lower temperature. Remembering that there is an optimum temperature for fluorescent lamp efficiency, it will be seen that below this optimum the argon-filled lamp may be more efficient than the krypton, whereas above it the position will be reversed. These differences are very slight at low current loadings, but at the higher current of the 5-ft. 80-watt lamp a krypton filling gives an appreciable increase in lamp efficiency.

Some recent experiments we have carried out on 5-ft. 80-watt Mellow lamps gave the following results :—

	Lamp Volts	Lamp Current	Lamp Watts	Total Lumens	Ambient Temp. deg. C.
Argon filling	106	.85 amp	80	2,800	23
Krypton filling	81	.85 amp	60	2,400	23

It will be seen that at 0.85 amp the use of a krypton instead of argon filling caused a reduction in lamp wattage of 25 per cent., whilst the reduction in light output was only 14 per cent. Unfortunately the krypton-filled lamp is more difficult to start than the normal lamp[15] and is also more costly to produce; furthermore, larger and consequently more expensive control gear is usually necessary for its operation. Factors such as these weigh rather heavily against its wider use.

(3.3) Transformation of ultra-violet radiation into light (Phosphor Efficiency)

It has been said earlier that the phosphor absorbs the ultra-violet radiation from the mercury discharge and emits visible light. Unfortunately the mechanism of the change itself causes reductions in energy and in addition the phosphors are not 100 per cent. efficient. Not every quantum of 2,537 Å radiation produces a quantum of visible light, indeed the ratio of effective incident quanta to the total incident quanta is between 80 per cent. and 90 per cent.

According to Planck's equation:—

$E_\lambda = \frac{h}{\lambda}$ where h = Planck's constant and λ = wave-length. E_λ, the energy possessed by one quantum of, say, 5,074 Å radiation is less than that of a quantum of 2,537 Å by a ratio of $\frac{2,537}{5,074}$ or $\frac{1}{2}$, and the ratio of energy between a 2,537 Å and a 6,343 Å quantum would be $\frac{2}{5}$. Thus the longer the wave-length of the emitted light the smaller will be the efficiency of the energy change from ultra-violet radiation.

In addition, the eye is not of uniform sensitivity to all colours; it responds more

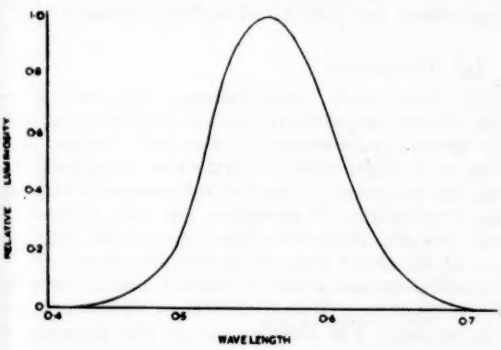

Fig. 5. Eye sensitivity curve.

Table 1.

Phosphor	Activator	Colour of Emission	Approximate Efficiency lm/w*
Calcium Tungstate	—	Deep Blue	16
Calcium Tungstate	Lead	Blue	28
Magnesium Tungstate		Light Blue	40
Zinc Silicate	Manganese	Green	80
Strontium Pyrophosphate	Tin and manganese	Green/Yellow	60
Calcium Halophosphate	Antimony and manganese	Blue-white Yellow-orange	45–70
Calcium Silicate	Lead and manganese	Orange Red	40
Cadmium borate	Manganese	Red	35
Magnesium Arsenate	Manganese	Deep Red	16
Magnesium Fluogermanate	Manganese	Deep Red	16

*For 5-ft. 80-watt fluorescent lamps.

readily to orange light than to red or blue. This sensitivity of the eye has been defined by the curve shown in Fig. 5. One watt of 5,074 Å radiation will represent about twice as much light as would 1 watt of 6,343 Å radiation, or 1 watt of 4,916 Å radiation; thus the spectral distribution of light emitted by the phosphor affects the efficiency of the lamp. Large amounts of red or blue reduce the efficiency whilst lamps rich in yellow or green light can have very high efficiencies. A good example of this is provided by the New Warm White and De Luxe Warm White lamps. Both have very similar colour appearances, but as the latter has a higher red content, its efficiency is only 60 per cent. of the former.

In addition, there are various other factors affecting the phosphor itself which can reduce the efficiency of the light production, e.g., phosphors at high temperatures do not luminesce as efficiently as at lower temperatures. The temperature dependence of the calcium halophosphates, an important group of phosphors which we shall discuss more fully later, is fortunately not significant.

It has been suggested that a phosphor can reach saturation point, at which further increase in ultra-violet radiation will not produce any further increase in emitted light. Experimental tests have shown that over the range of ultra-violet intensities normally experienced in fluorescent lamps, such effects are slight for phosphors in general use[17].

(4) Phosphors

In 1938 fluorescent lamps gave 30-40 lm/w, using blended phosphors which included: zinc beryllium silicate, zinc silicate, magnesium tungstate and, later, cadmium chloro phosphate, etc.[18, 19]. The spectral composition of these early lamps varied considerably, owing to the difficulty in matching different batches of phosphors, and the maintenance of efficiency during life was poor. Since that time extensive research work has been devoted to improving existing types of phosphors, but more particularly on developing new ones. Very many new phosphors have been reported but relatively few have proved of real use because of the severe demands made upon them.

The main types of phosphor in use to-day are shown in Table 1, and of these the most useful is calcium halophosphate, which is used for producing a variety of near-white colours ranging from blue to orange. The development of this phosphor in

1942([20]) was a most outstanding contribution and it is now used extensively. Besides its colour range it is capable of high luminous efficiency and maintenance and can be prepared simply from relatively cheap raw materials. Some of the other phosphors listed in Table 1, which give more saturated colours, are used in limited quantities to improve the colour rendering properties of halophosphate lamps and also to produce coloured lamps. They can also be used to obtain white colours by blending.

Fig. 6 shows improvements in luminous efficiency and maintenance that have been effected, and Fig. 7 the spectral distribution of some of the phosphors in Table 1([21]).

(4.1) Preparation of Phosphors

Most phosphors are prepared in the same general way; the raw materials are milled together in either the wet or dry state in order to ensure an intimate mixture, and this is then fired in a suitable furnace at a temperature between 700-1,200 deg. C. depending on the type of phosphor. The resulting lightly sintered mass is then ground to a particle size of about 5 microns.

Many conditions must be satisfied if phosphors of the best possible characteristics are to be produced. The raw materials must be of the highest chemical purity; the presence of extremely small amounts of certain heavy metals, for example, reduces considerably the phosphor brightness.

To obtain intimate mixing of the matrix with the activators and to give a finished phosphor of small particle size, the raw materials must be as finely divided as possible. The amount of activator present and its valency state influence considerably the colour and efficiency of the phosphor. For example, calcium halophosphate activated by

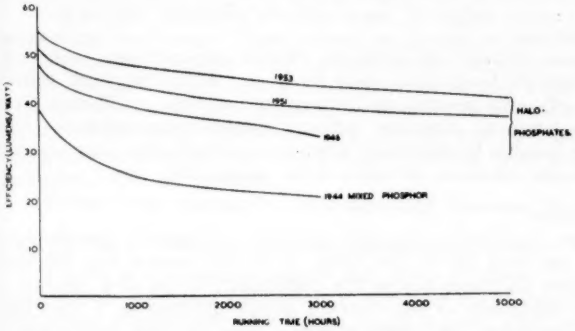

Fig. 6. Curves of efficiency through life of 80-watt Daylight fluorescent lamps.

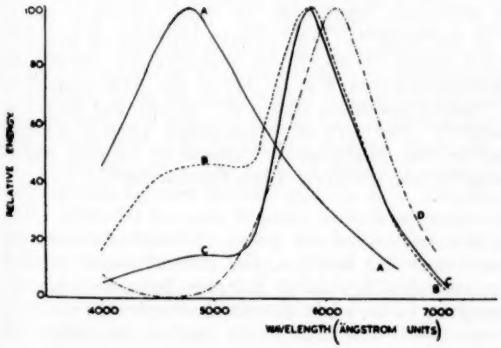

Fig 7. Spectral energy distributions of calcium halophosphates and calcium silicate

A. Light blue
B. Daylight
C. Warm white
D. Calcium silicate, Pb.Mn.

antimony alone fluoresces blue, but when manganese is present as a second activator the colour becomes progressively more red as the amount of manganese is increased. The antimony must be present in the trivalent state and manganese in the divalent and, in order to ensure this, air must be excluded during the firing process otherwise oxidisation, especially of manganese to the tetravalent state, can occur with subsequent appearance of a pink to brown body colour and loss of brightness.

The firing temperature is such as to effect a compromise between the development of maximum brightness and the production of a strongly sintered material which it is impossible to grind.

(4.2) Testing of Phosphors

In addition to the chemical and physical tests which must be carried out on the raw materials to ensure that they are of the required purity, it is also necessary to test the finished phosphor. Although finally it is best to make up a batch of lamps, simple tests have been devised which give indications of the performance of any phosphor batch. These include (a) Brightness tests in which the light emitted from a sample on irradiation with 2,537 Å radiation is compared photo-electrically with known standards, (b) Colour tests—the red, blue and green components of the sample can again be compared with standards, (c) Physical tests of particle size, bulk density, etc., which indicate the constancy of the phosphor and its suitability for lamp coatings.

(4.3) Characteristics of Phosphors

The number of phosphors which are suitable for fluorescent lamp manufacture is comparatively small. The general characteristics which are necessary are discussed below.

(4.3.1) *High Phosphor Efficiency*

Since 1938 the luminous efficiency of lamps has steadily improved and to-day the New Warm White and Daylight lamps give about 60 lm/w. Much has been written on the highest theoretical efficiency possible and values from 60 lm/w to 80 lm/w have been calculated for white lamps of somewhat different spectral compositions. Still higher efficiencies may be possible by continued attention to details, but there are certainly no signs that any major advances are likely in the near future.

(4.3.2) *Phosphor Maintenance*

Perhaps of even greater importance than high initial lumen output is the maintenance of efficiency during the long life of the lamp. It is well known that the light output of a fluorescent lamp decreases during life, particularly in the first 100 hours. Some of the decrease is attributed to the mercury which deposits as a thin film on the tube coating and prevents the ultra-violet radiation from reaching the phosphor. This deposition on the phosphor surface is aggravated by traces of alkali in the phosphor or on the glass surface of the lamp[24]. The relative inertness of the halophosphates and their freedom from traces of alkalis are probably the reasons for their good maintenance. Poor maintenance may also be due to the close association of phosphor and mercury which makes possible a chemical reaction and results in a change of valency of the activator[22]. The very low wave-length 1,850 Å mercury radiation, which is also produced by the discharge, is capable of causing photochemical decomposition of the phosphor and rendering it less fluorescent[23].

(4.3.3) *Phosphorescence*

Most phosphors continue to emit light when the source of excitation has been removed; this afterglow, which continues for hours in the case of some sulphide phosphors, is only a fraction of a second with calcium halophosphate, for example. It is useful for fluorescent lamp phosphors to have a bright, short afterglow to minimise the stroboscopic effect which occurs when discharge lamps operate on alternating

current supplies. Generally, red-emitting phosphors have a longer afterglow than blue ones. The afterglow of some phosphors has been improved, an example being zinc silicate, by the inclusion of arsenic; alternatively, traces of heavy metals reduce the afterglow of many phosphors.

(4.4) Application of Phosphor to Lamp

Numerous methods have been used for coating the lamp tube with a thin layer of phosphor: these include:—

(a) Dusting the powder on to a tube which has previously been coated with an adhesive binder such as sodium silicate or phosphoric acid.

(b) Electrostatic deposition of the powder on to the tube.

(c) Coating the tube with a suspension of the phosphor in a medium such as sodium silicate, ethyl silicate or nitrocellulose solution.

All these methods have such disadvantages as non-uniformity of layer, embrittlement of the glass or residues of substances detrimental to lamp efficiency and maintenance. The method (c) using nitrocellulose has proved most suitable and is now used extensively.

(5) Lamp Manufacture

The need to mill the phosphor to the required particle size for the best coverage of the tube wall and the subsequent treatment in the manufacture of the lamp tend adversely to affect the phosphor and the luminous efficiency of the finished lamp. Lamp-manufacturing techniques always cause some loss in initial lamp efficiency, but they are so devised that this loss is reduced to a minimum.

It is evident, therefore, that the quest for higher values of light output of existing lamps takes two forms. Firstly, efforts are directed at increasing the potential efficiency of the phosphor, and secondly, manufacturing techniques are sought to reduce still further the loss in light output due to lamp processing. Although initial light output has been mentioned, the desirability to improve lumen maintenance is acknowledged, and in this respect the lamp processing can improve the phosphor maintenance by, for example, depositing on the inside of the phosphor layer chemicals which absorb the damaging 1,850 Å radiation.

We may now examine the manufacturing processes, dealing with each in turn.

(5.1) Milling of Phosphor with Nitrocellulose and a Solvent

Directly after firing, the particle size of the phosphor is too large for its immediate application to the tube; a phosphor in this state would appear rough and a poor lamp appearance would result. Further, a rough coating gives wide variation in phosphor layer thickness and provides an irregular surface on to which mercury is easily condensed and absorbed. Before tube coating is attempted, therefore, the phosphor particle size must be reduced and a milling process is used almost universally. The phospor is placed in large mills with the nitrocellulose and a solvent. After a charge of grinding balls has been added the mill is rotated at a predetermined speed for a definite time. In order to reduce to a minimum the amount of wear on the balls and mill, which will contaminate the powder, these are made as hard as possible. This applies particularly to the balls, as there is a much greater grinding action between ball and ball than between the balls and the mill. Porcelain or flint balls are most commonly used. Mills for the past 10 years have been exclusively of porcelain or other forms of fired ceramic, but because of the difficulties of firing such large masses of ceramic (mills with capacities in excess of 100 gallons are common), fabricated iron mills with internal linings of porcelain or quartz tiles are coming into use. The amount of milling a phosphor receives must always be a compromise between tube appearance and lamp efficiency.

(5.2) Application of Phosphor Suspension to the Tube Wall

The phosphor is deposited on the inner surface of the tube by either welling up or pouring down the inside of the tube the phosphor suspension; the tube is then allowed to drain and dry, when the solvent evaporates and leaves a thin coating of phosphor and binder. The amount of phosphor per unit volume of suspension, the suspension viscosity, the temperature and humidity of the drying room and the rate at which the solvent vapour is extracted, can all affect the thickness of the phosphor layer and are therefore rigidly controlled or intercompensated to maintain the layer at optimum thickness.

A fluorescent coating that is too thin does not utilise enough of the ultra-violet radiation and when too thick absorbs an appreciable amount of the visible radiation in its own thickness. It is common test procedure to check the total powder weight on the tube, but as a coating for maximum efficiency composed of fine particles will be thinner and less heavy than one composed of larger particles, other measurements such as reflection factor, transmittancy and absorption factor of the coating are necessary[17].

(5.3) Tube Firing

It is necessary to remove from the phosphor layer the nitrocellulose. This is done by heating the coated tube to the temperature at which the nitrocellulose decomposes to gaseous products, the nitrocellulose being so chosen that this occurs below the softening point of the glass tubing. The phosphor, which during preparation may have been furnaced at as high a temperature as 1,150 deg. C., experiences at this stage a temperature close to 600 deg. C. However, this is sufficient to affect it adversely due to its changed circumstances. Firstly, the decomposition of the nitrocellulose produces oxides of nitrogen, which at this temperature are highly reactive. Secondly, the glass, a large area of which is in contact with the phosphor, can give rise to an inter-reaction and, lastly, if the baking furnace is gas fired the products of combustion may also be reactive. The decomposition of the nitrocellulose is noteworthy. If the heating up of tube in the furnace is slow the binder tends to "burn" rather than "explode" and, even though air and/or oxygen is blown into the tube, carbon is formed and once produced is difficult and often impossible to remove completely.

(5.4) Electrode Sealing

The sealing in to the end of the lamp of the electrode assembly is normally carried out with the tube rotating in a vertical position, and by directing gas flames, sometimes boosted with oxygen, on to the wall of the tube close to the electrode assembly. This operation causes the air inside the tube to become heated, and it therefore rises. In so doing air is drawn in through the bottom of the tube and as this is situated close to the gas flames products of combustion may be drawn through. These adversely affect the lamp by being deposited on the phosphor surface, or, as with some oxides of sulphur, by reacting chemically with the phosphor. This effect is most pronounced when the first end of the lamp is being sealed in, as the top end is open. This "flue" effect may be combated by providing over the top end of an open tube a jet of air which plays down into the tube and so prevents a convection stream forming. Such a practice must be done carefully as an excessive down pressure will distort the seal shape when the glass is mobile.

(5.5) Lamp Exhaust

When the lamp is exhausted it is necessary to heat the envelope to 500 deg. C. in order to free occluded gas. Also, the electrodes are heated in order to outgas the emissive material with which they are coated; this results in quantities of carbon dioxide being evolved, together with small quantities of oxides of nitrogen from the

nitrocellulose binder which is included in the emissive material. Under these conditions chemical reactions can occur with the phosphor. It has been found[25] that oxygen, for example, can act as a quenching molecule. Rapid removal of these harmful contaminants is desirable and is achieved by either placing the lamp on a high vacuum system or by using a flushing technique. Owing to the high cost of using spectrally pure argon as a filler gas, a cheaper grade with a small nitrogen impurity is sometimes used and it has been found that lamps containing this so-called "degraded argon" give improved lumen maintenance characteristics[26].

After the lamp is sealed off and subsequent to capping it is usually operated for a short time. This cleans up traces of impurity still present in the lamp by the gettering action of the lamp coating and the cathode material.

(6) Possibilities of Further Increases in Lamp Efficiency

It has been shown that longer arc length means higher lamp efficiency. With bi-pin lamps it is possible to dispense with a cap and make contact through projecting connector pegs which are rigidly sealed into the ends of the glass envelope; this and the use of shorter caps permit increases in arc length within the present dimensional limits, which give small increases in lamp efficiency, particularly with the shorter lamps.

If efficiencies higher than the present New Warm White lamps are required, these can be achieved at the expense of colour rendition and such a lamp might be acceptable for such purposes as street lighting. Its colour rendering properties would still be far superior to sodium and uncorrected mercury discharge lamps.

Practical, present-day efficiencies are consistently below the levels achieved under the best laboratory conditions by about 2 lm/w for 5-ft. 80-watt lamps. It is to be expected that this disparity will progressively decrease with the elucidation of the factors which are responsible for depressing the practically obtained values.

Attention to detail in phosphor preparation will continue to give small efficiency increases. If the good colour rendering lamps are to be improved a good red emitting phosphor is required, but to date all phosphors of this type have drawbacks. Theoretical considerations indicate that our present phosphors are 80 per cent. and 90 per cent. efficient, which makes impossible any revolutionary advances.

It is evident that although a great amount of empirical data on the performance and operation of fluorescent lamps has been accumulated during the last 20 years, there are still some benefits to be secured by a close consideration of the fundamental processes involved and the application of these to the factory techniques necessary for the continuous production of these light sources. As with many modern industries achievements have well outrun the explanations, and the next major step forward may arise from a serious analysis of the ground already covered.

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Discussion

DR. J. W. STRANGE: I wish first to congratulate the lecturer on his presentation of the paper. He has appreciated that the spoken version must be very different from the written version and in so doing has kept our interest throughout. My comments must, however, refer mainly to the written paper. In introducing this discussion I am probably an unsuitable choice. I have now completed about 14 years "hard labour" on the subject of fluorescent lamps and for this reason I take a detailed interest in the subject, which is probably very different from the bulk of the audience. The sort of paper that I would be interested in would almost certainly be boring to the majority of the listeners, whereas the paper here presented gave an interesting survey of the simple basic facts of fluorescent lamp manufacture.

The title does, however, lead one to suppose that it will be at least an up-to-date and critical survey of the factors affecting the efficiency of fluorescent lamps and in particular the problem of lumen maintenance which it is rightly stated as one which is of primary concern to the user.

In the paper only one short paragraph (4.3.2) is devoted to this subject and two of the three references are nine years old. A number of excellent papers have been written on this subject and published recently, particularly by Dr. Lowry and his associates, which have helped a great deal to reduce the mass of information to some order, if not to explain it fully.

The equation $L_o - L_t = A(1-e^{-at}) + B(1-e^{-bt}) + C(1-e^{-ct})$ described the data in the form of a reaction rate equation, when L_o = initial efficiency in lm/w, and L_t = efficiency at any time. There are three terms representative of three impurity processes and three exponents governing their rate. It may be said that almost anything can be described with three exponential terms but the remarkable thing is that the required exponents have remained almost constant over a number of years and the size of the terms has represented the steady improvement. This is so not only of American data but also of thousands of lamps which we have life-tested in this country.

Reference may be made to a recent paper given at the American National Technical Conference of the I.E.S. in September, where Homer, Butler and Bergin gave an interesting extension of Lowry's work to cover phosphors stabilised by the removal of a surface layer.

The causes underlying these changes are complex ones, and while I wish to be

constructive as well as critical it would need a second paper to do justice to the subject. Quite a number of facts are already established about the nature of the three processes of the Lowry equation and on such facts must be constructed the final explanation. One such fact is, for example, the effect produced by the addition of a small amount of an oxide of antimony. This in the case of a silicate phosphor has a marked effect in reducing the B process. Traces of carbon left from the combustion of the binder can have an equally important effect in increasing the B process. One point of considerable interest is the effect of lamp loading of these different processes. In general the higher the loading the greater the rate at which they go to completion. This means that with the steady improvement of the overall position the higher loaded lamps like the 80-watt have shown a greater gain than the lower loaded lamps over the early part of their life. This is in line with the understanding of the Lowry equation as something similar to a chemical reaction.

There are quite a number of statements made in the paper which lack support in the way of evidence. For example, the quite tricky compromise between efficiency and lumen maintenance based upon the pressure of the gas filling is one that presents some difficulty because it can be dependent upon a number of factors and upon extensive life-test information, and yet we are faced with a simple statement that the optimum figure is about 3 mm. Could the authors amplify this?

In paragraph 4 the reference made to the type of phosphors used rather lead us to suppose that phosphor layers made of blends are not now in use except in very limited applications. In practice, phosphors are widely used in blend form for the manufacture of the so-called de luxe colours where the use of separate phosphors gives control over the spectral distribution of the lamp.

In paragraph 5.5 reference is made to the improved characteristics which result from the use of "degraded argon." This is derived from a patent application which is not necessarily good evidence. Have the authors any facts to support these statements?

In conclusion I feel the authors have written a paper which will probably be read with interest by those who are not very familiar with the subject but can only be read with disappointment by those whose primary concern is to deal with the problems raised. It is no compensation for this disappointment to be told in the last sentence that "the next major step forward may arise from a serious analysis of the ground already covered." The authors in the next paper may like to take up their own challenge.

Mr. H. G. JENKINS: It is at least questionable if the colour characteristics of fluorescent lamps are preferred to those of filament lamps; the high efficiency and long life of fluorescent lamps are almost certainly their main attractions.

Would the authors not agree that the fluorescent lamp would be even more attractive if its life were related to its efficiency in an inverse sense? One wonders if it is true to say that climatic conditions and supply voltages largely dictate the present fluorescent lamp design. It would appear that climatic conditions hardly enter the picture at all, since the lamps are used largely indoors and frequently in enclosed fittings. The chief supply voltages in America are about half the voltages generally available in this country, yet much the same design of lamps is available here as in the States. The British 5-ft. 80-watt high-loaded lamp was developed to meet a war-time need for a high wattage rating. A choke for H.P.M.V. lamps was already available and the lamp was designed largely to operate from this existing gear. It is not without interest to note that the Americans have now followed the British lead and have recently introduced high-loaded lamps into their range.

The authors have made a brave attempt to sort out the complex interrelationships

between efficiency, mercury vapour pressure, arc current and tube diameter. It is not quite clear if the curve in Fig. 3 of the paper adds much to the information given in Figs. 1 and 2. If the intention was to show the "wall effect" on efficiency, it might have been better to have made the measurements in Fig. 3 at constant current density.

In discussing efficiencies it should not be forgotten that the theoretical efficiency of a temperature emitter is higher than the 60 and 80 lm/w calculated for white fluorescent lamps of spectral distributions similar to Colour Matching and British Daylight colours. The reason for this is that temperature emitters are not subject to the inevitable and high transformation losses of the fluorescent lamp. It is noteworthy that the theoretical value for white light, assuming no infra-red or ultra-violet losses, is of the order of 250 lm/w. The limitation in achieving these high efficiencies from temperature emitters is, of course, the absence of suitable refractory materials for the filaments.

The authors refer to a possible high-efficiency lamp which might compete with sodium and H.P.M.V. discharge lamps for street lighting. It is well known that a green fluorescent lamp can be made at an efficiency comparable with that of a sodium lamp, but the colour of this would be entirely unacceptable. Perhaps the authors would be more specific on this point.

The authors have given a most useful review of a subject of general interest. They have suggested that the last word has not yet been said on fluorescent lamps, but they do not lead us to expect revolutionary advances in the future. It is probably true that the present design of lamp is unlikely to yield other than small gains in performance and these gains become increasingly difficult to win. Bearing in mind the analogy with the incandescent filament lamp, one visualises lamp engineers still struggling to achieve the last fraction of a lumen per watt in 30 years' time. The authors have, perhaps wisely, kept away from vague speculation on the future; they certainly have not said anything to suggest the possibility of an entirely new light source arising, which would render obsolescent the fluorescent lamp and other conventional light sources.

MR. H. HAZEL: The claim has been made that it is possible to "revitalise" fluorescent lamps, apparently without removing the caps. Could the authors comment on this?

MR. J. B. COLLINS: Could the authors say anything about the use of phosphors which fluoresce under the longer wave-length u.v. to produce visible light.

THE AUTHORS: We would like to thank those who have contributed to the discussion. In preparing the paper we were aware of the difficulty of trying to write an "expert paper" which would be acceptable to those with less detailed knowledge and we have purposely erred on the side of simplicity.

Replying to Dr. Strange, the Lowry equation is useful, but it is necessary to adjust the values of the constants to the conditions of manufacture. Although there is much published evidence that the use of antimony trioxide reduces the B process of the Lowry equation, our experiments both in the laboratory and in bulk manufacture show that the improvement in lumen maintenance is much lower than American data suggest. We are not implying that the American or our own results are faulty, but that the different conditions of manufacture are the cause of the discrepancy.

Concerning argon filling pressure, we would agree that the choice is not a simple matter but necessitates involved analysis of data from efficiency maintenance records. As has been indicated in this paper, the pressure of gas in a lamp affects many of its

characteristics; initial lumen output and maintenance of lumen output are but two, other dependent variables being life, starting characteristics and operating voltage. The effect of pressure on each of these has been determined separately and an attempt could be made to derive from this data a pressure giving the "best" general effect. Two problems arise; how to combine such separate results to give a general optimum and the fact that this choice of "best" depends on the order of preference in which the effects of gas pressure are placed. The final test is one of trial and error, to determine a pressure which gives a standard of performance which is acceptable for all lamp characteristics. Nothing could be gained by specifying this pressure very accurately, since due to its nature as an arbitrary compromise it is to be judged by its effects in relation to local manufacturing conditions of, for instance, efficacy of cathode preparation and reaction of phosphor to operating conditions. Also there is obviously a limit to the accuracy with which commercially produced lamps can be filled.

Regarding the use of blended phosphors, we agree with Dr. Strange that as De Luxe lamps are introduced more phosphor blends will be used; nevertheless a very high proportion of present manufacture will be made with straight halophosphates. With regard to degraded argon, we have found that when a nitrogen content is included in the filler gas, although there may be a slight fall in initial luminous efficiency the lumen maintenance is improved and this type of filler gas is at present used. The cost of "degraded argon" is also much less than pure argon and there is, therefore, an economic advantage in its use.

In reply to Mr. Jenkins's suggestion that the fluorescent lamp would be even more attractive if the life were related to its efficiency in an inverse sense, with the present cost of labour for lamp replacement I doubt if users would support him. Concerning his remarks that the 80-watt lamp was designed to operate on an existing choke in use with H.P.M.V. lamps, we recall that considerable difficulty was experienced due to choke breakdown as the voltage surges developed in the fluorescent circuit were not present in the H.P.M.V. circuit. We would agree with Mr. Jenkins's suggestion that in Fig. 3 measurements at constant current density would have been preferable. Our proposals regarding fluorescent lamps for street lighting are for a 5 ft. 80-watt lamp giving approximately 65 lm/w at 100 hours and having a colour approximately that of the present New Warm White.

In reply to Mr. Hazel, we understand that attempts have been made to revitalise lamps without removing the caps, by high frequency heating for example. This does little more than distil mercury off the phosphor and the revitalisation is temporary as the lamp will revert to its former efficiency very quickly, certainly within 100 hours. In addition it should be remembered that the natural death of a lamp occurs when the emissive material has been lost from the cathode and as with human beings no amount of revitalisation can delay the inevitable.

Mr. Collins has raised an interesting point with regard to the longer wave-length ultra-violet in the discharge producing visible light. From Planck's equation the efficiency of energy transfer from 3,650 Å instead of 2,537 Å would be more efficient, but unfortunately phosphors which respond to the lower wave-length ultra-violet are not as stable as those at present in use. In the lamps specifically designed for good colour rendering it is desirable to absorb, and if possible re-emit as light of a longer wave-length, the violet mercury line present in the discharge. This has already been attempted successfully with lamps of De Luxe Warm White type, but the emphasis has been to remove the violet mercury line rather than utilise it to achieve higher efficiency.

Additions to the List of Members

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Printed by ARGUS PRESS, LTD., Temple-avenue, and Tudor-street, London, E.C.4. England